

# **Modeling For Ecosystem Management in Minnesota Pine Forests**

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# MODELING FOR ECOSYSTEM MANAGEMENT IN MINNESOTA PINE FORESTS

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## Abstract

Ecosystem management implies a concern over time periods of tens to hundreds of years for sites on a scale of tens to hundreds of hectares. Decision makers need to be able to model the likely consequences of alternative management strategies at these temporal and spatial scales. They therefore require models that can be constructed quickly and cheaply, that capture the key components of the ecosystem, that respond plausibly to management actions, and are easy to explain, modify and understand. This paper presents the frame-based modeling paradigm as a response to these needs. Frame-based modeling is used to examine the effects of soil, weather, fire and deer population density on management of the white pine ecosystem in northern Minnesota.

The management objective is to maintain white pine forest. The paper describes how current understanding of seedling establishment, tree growth, competition, herbivory and the effects of fire and high winds, can be captured at a consistent level of resolution in a model that can be presented, completely, in a few pages of text. The paper goes on to describe how the model was tested at three sites in northern Minnesota, and was then used to explore alternative management strategies.

Our results confirm that it is comparatively easy to maintain a forest in early successional stages by burning or clear-cutting, and in late stages by suppression of fires and control of cutting. Establishment and maintenance of mid-successional stages, such as red and white pine, is much more difficult and requires a finely-tuned balance between natural disturbance and management action. For example, the pine forest was only maintained on average for 117 years out of 1000 years (average among 1000 simulated stands) on poor soil with high fire frequency and high deer density. When the deer population was low, when all wild fires were suppressed, and when prescribed ground fires were used to promote pine establishment, years in pine was 804 out of 1000 years. The model provides guidance for management decisions to maintain the desired conditions.

The paper draws some conclusions from this particular modeling exercise that are likely to be generally applicable. For example, the modeling exercise illustrates limits

to what management can hope to achieve, the importance of maintaining strategies over long time periods, and the difficulties of predicting and measuring success when the time horizon is hundreds of years. © 1997 Published by Elsevier Science Ltd. All rights reserved

**Keywords:** ecosystem management, pine forest, frame-based model, fire, deer browsing, white pine.

## INTRODUCTION

Application of ecosystem management in forested landscapes is dependent upon adequate knowledge of the structure and functioning of the ecosystem under consideration. What constitutes adequate knowledge is a highly relevant question. The complexity of forest ecosystems allows scientists to possess detailed knowledge of ecosystem processes for only a few locations where case studies have been done. Thus, managers are often faced with making decisions that affect an entire landscape with only rudimentary information on ecosystem parameters for the vast majority of the area involved. Models that simulate forest succession under various conditions that may be of interest to managers often require a high level of detail. For example, several models incorporate many parameters such as nitrogen mineralization rates, shading of trees by one another, competition for water and local effects of seed rain. These, which are generally on the scale of 10×10 m, include JABOWA (Botkin *et al.*, 1972) and its derivatives FORET (Shugart & West, 1977), LINKAGES (Pastor & Post, 1985), and the new spatially explicit model, SORTIE (Pacala *et al.*, 1993). These models are being used extensively for research; however, the requirement for inputs such as soil carbon and nitrogen concentrations and seed rain, which are labor-intensive to obtain, makes them impractical in the context of management. It appears that models requiring fewer details, but incorporating relevant and functional parameters (as in Noble & Slatyer, 1980) and processes on a larger spatial scale, are needed for practical applications of ecosystem management at the landscape level.

This paper describes a parsimonious model of forest succession that was developed to aid in restoration of the pine forest ecosystem in Itasca State Park in northwestern Minnesota. The model uses expert systems technology and the artificial intelligence concept of a frame (Starfield *et al.*, 1993) to analyze the state of a forest stand, generally on the scale of 1–10 ha. The model is not deterministic and can be employed with a large number of replicates to derive probabilities that stands will follow a certain successional pathway under given circumstances. Categories, such as poor, medium and good soil or low and high rainfall (see model description below), are used to build a model that uses simple inputs widely available to managers. Data from ecosystem classification systems (ECS), which are now being carried out on US National Forest Service lands (Russell & Jordan, 1991) and Minnesota Department of Natural Resources lands (J. Almendinger, pers. comm.), are rapidly being made available on geographical information systems (GIS). These GIS databases show the landscape as a collection of stands with different attributes (such as soil quality) that relate to species composition and productivity. Thus, data of the type required for the model presented here—low level of detail but large areal extent—are likely to be available in the near future.

The need for a simple model that could be used to evaluate management strategies for pine restoration in Itasca State Park became apparent during recent discussions with resource planners and managers. Due in large part to repeated wild fires and probably to low deer populations, forests of white pine *Pinus strobus*, which usually contain a component of red pine *Pinus resinosa*, were a major part of the pre-European settlement forest base of the state, and occupied about 1.4 million ha (Frelich, 1995; Tester, 1995). Today, only about 0.2 million ha of white and red pine forest exist in Minnesota, most of which is second growth. Primary forest remnants, that have never been logged, total only 0.022 million ha, or 1.6% of the pre-settlement total (Frelich, 1995). Pine stands within Itasca State Park are included in this remaining small fragment of primary forest. However, regeneration of the great pine stands has been virtually nonexistent since the Park was established in 1891. As early as the 1930s, problems with pine regeneration were noted in unpublished reports. In the 1950s, Hansen & Brown (1950) and Hansen & Duncan (1954) also reported problems with pine regeneration, and identified heavy brush, white-tail deer *Odocoileus virginianus* browsing and absence of fire as the causes. These findings agree with many other studies that the relatively low fire frequency and high deer populations in the modern forest commonly cause regeneration failure in white pine (Maissurow, 1935; Hough & Forbes, 1943; Cwynar, 1977).

Wildfires within Itasca Park were practically eliminated by 1922; however, prior to this time, they were common. During the period 1650–1900, pine forests in

Itasca and most of northern Minnesota were influenced by a natural disturbance regime with intense stand killing fires at 150–200 year intervals, and intervening light surface fires at intervals of 13–38 years in a given stand (Frissell, 1973; Heinzelman, 1981). During the settlement and logging period, 1900–1922, there was a slight increase in frequency of both stand-killing and light surface fires, followed by reduced frequency until the current time (Anfang, 1972). During the recent absence of fire, succession has proceeded to shade-tolerant species such as white spruce *Picea glauca* and balsam fir *Abies balsamea* on sites with poor soil and to northern hardwood species such as sugar maple *Acer saccharum* and red maple *Acer rubrum* on sites with good soil (Webb, 1988). The rate of succession is increased not only by a lack of regeneration of white and red pine, but also by windstorms, that preferentially remove white and red pine, because they are usually the largest and tallest canopy trees in older stands (Foster, 1988; Webb, 1988).

It is apparent that the forests of large white and red pines, one of the major attractions of Itasca State Park, will largely disappear unless managers intervene. In a survey conducted by McCool (1966), the use of prescribed burning for vegetation management in Itasca State Park was viewed favorably by administrators and scientists because it is a natural process and played an important role in presettlement forests. The use of tree cutting was viewed by some research scientists as acceptable, but only during the initial stages of red and white pine regeneration and not on a continuing basis, because it is not a natural factor in ecological succession. The use of herbicides was generally viewed negatively by each group. Fire and browsing by deer are the only natural ecological processes which can be manipulated by managers. This model provides a means for evaluating these natural processes and provides insights for managers on the effectiveness of cutting and other manipulations. At the same time, it allows one to examine how factors not controlled by managers, such as soil type and windstorms, affect succession.

## STUDY SITE

The model is based on forests of northern Minnesota at about 47° N latitude. These forests are within the Minnesota Pine Area of the Hemlock—White Pine—Northern Hardwoods Region of Braun (1950), although hemlock is absent. This area has a continental climate with mean annual precipitation of about 640 mm and a mean annual temperature of about 3.7°C (Kuehnast, 1972).

Historically, two major successional cycles have occurred in upland forests of this region. On poor to medium-quality soils, which tend to be thin and/or coarse sandy soils, fire was the dominant type of natural disturbance (Frissell, 1973; Heinzelman, 1973; Heinzelman, 1981; Clark, 1988). Even-aged stands dominated

by jack pine or aspen, or a mixture of the two developed after stand-killing fires, which occurred at intervals of 50–200 years (Frissell, 1973; Heinselman, 1981; Frelich & Reich, 1995). Even-aged stands of jack pine or aspen can burn before the original cohort dies, regenerating even-aged jack pine from serotinous seeds (Rudolph & Laidly, 1990) or aspen from root sprouts and long-distance seed transport from other stands. Alternatively, even-aged jack pine or aspen can be invaded by white pine, followed by invasion of white spruce and balsam fir, although occasionally spruce and fir invade even-aged post-fire stands directly without an intervening white pine stage (Maissurow, 1935; Buell & Niering, 1957; Heinselman, 1981; Frelich, 1992). Old-growth multi-aged white pine stands may be maintained for several centuries by surface fires that periodically remove understory spruce and fir without killing the large pines (Frissell, 1973; Heinselman, 1973). Old white pine stands may burn catastrophically and return to even-aged jack pine or aspen (Heinselman, 1973; Cwynar, 1977; Whitney, 1986), or blow down, which accelerates succession to spruce and fir (Stoeckeler & Arbogast, 1955; Foster, 1988).

The second major successional cycle, which occurred on good soils, contrasts sharply with that on poor soils. Fires were much less common, so that wind was, and still is, the dominant form of natural disturbance (Canham & Loucks, 1984; Whitney, 1986; Webb, 1988; Frelich & Lorimer, 1991). Aspen stands originate after rare stand-killing fires and succeed rapidly to white pine or to northern hardwoods such as sugar maple. If white pine invades first, then succession to northern hardwoods will proceed, but if northern hardwoods invade first, then the white pine stage is skipped, since white pine is not shade-tolerant enough to grow under northern hardwoods (Hough & Forbes, 1943; Wendell & Smith, 1990). Once northern hardwoods are well-established in a stand, conversion back to aspen or white pine is very rare, because northern hardwood litter is not flammable, making fires quite rare, and windstorms that level the canopy simply release abundant understory hardwoods from suppression (Stearns, 1951; Dunn *et al.*, 1983; Lorimer & Krug, 1983; Frelich & Lorimer, 1991).

## DESCRIPTION OF THE MODEL

Forest patch models (e.g. FORET, Shugart & West, 1977) are generally good examples of a bottom-up modeling approach; the model is developed from the bottom of a hierarchy that starts with fundamental processes, such as nutrient cycling, without much concern (at least at that point) about how the model will be used. In contrast, we use the top-down approach of starting with the management questions and developing the simplest model that might help to answer them. We restrict ourselves, in this paper, to a single stand,

although we recognize that interactions between stands will be important. Management questions are concerned with the successional dynamics in that stand, so we begin by defining the successional stages. These depend on soil type, so we first recognize three categories that characterize the variability across the study area: we call these poor, medium and good soils. On poor soils, jack pine is the pioneer species and there are potentially two successional stages: in one, red and white pine are common, while the other is dominated by northern coniferous trees, such as white spruce and balsam fir; we call this the Jack Pine–Pine–Spruce cycle. On good soils, aspen is the pioneer species, a stage in which white and red pine are common also can occur, and the third stage is one where hardwoods such as sugar maple, basswood *Tilia americana* and associated shrubs are dominant; we call this the Aspen–Pine–Maple cycle. On medium soils, either cycle can occur.

At this point, our management model looks as though it will reduce to a traditional markov matrix model of succession (Getz & Haight, 1989)—one in which we specify transition probabilities from one successional stage to another and deduce the steady state proportions of time spent by the system in each of the stages. Unfortunately that kind of model does not answer the management questions that we have posed. State-and-transition models (Westoby *et al.*, 1989) provide a conceptual basis for addressing management questions, but do not mechanistically model either the external forces, such as drought, fire, and wind, that drive succession or the management actions, such as fire and deer control, that might mediate succession. Instead of specifying transition probabilities or providing a conceptual framework for management options, we need to model successional mechanisms. The frame-based modeling paradigm (Starfield *et al.*, 1993) enables us to do this simply and effectively. Briefly, this works as follows.

The overall simulation model consists of five 'frames' corresponding to the key successional stages. At any time in a simulation, only one frame is operational. Within each frame we have built a simple simulation model of the key mechanisms that will determine whether the patch switches from that frame to another. When a switch occurs, the overall model changes frames and the simple model that we have built in the new frame replaces the model that was operating in the old frame. In this way, we partition the modeling problem into a series of simple models, one for each frame. The models are simple because we can concentrate on what is important, in the sense of determining succession, within each stage or frame. For example, natural fires are very important in the Spruce Frame, but are ignored in the Maple Frame.

Succession takes place over a time scale of tens or hundreds of years; therefore, we chose a time interval of 10-years for this frame-based simulation. For each 10-year interval, we characterize the precipitation as

'unusually dry' or 'normal'. A ground fire can be prescribed by management at the beginning of the decade, and we assume that natural fires, if they occur, can be stopped by management. Natural fires are characterized as either ground or crown fires. High winds, if they occur during a decade, can blow down an entire generation of old pines. Deer can browse on pines less than 2.1 m high. Deer populations of less than 2 per km<sup>2</sup> are categorized as low, populations from 2 to 5 are categorized as medium, and populations of 6 or more deer per km<sup>2</sup> are categorized as high (Alverson *et al.*, 1988). Maple and spruce stands can be clear cut and burned. Spruce budworm outbreaks can occur in older spruce stands. Mature pine trees can be harvested.

All of these influences on succession are represented in the separate frame models in a partly qualitative and partly quantitative way. Quantitative effects are described by equations, and qualitative effects by rules (Starfield *et al.*, 1989). The following is a full description of the frame models.

## ASPEN-PINE-MAPLE SUCCESSIONAL CYCLE

### Aspen Frame

Variables include age of aspen, height of the maple understory, height of pine trees, and time since the last fire. Pine and maple seedlings establish themselves under the following conditions:

1. On good soil, with a probability of 0.5 if the aspen are 20 years old, and with a probability of 1.0 if aspen are 30 or more years old;
2. On medium soil, with a probability of 0.5 if aspen are 10 years old, and with a probability of 1.0 if aspen are 20 or more years old;
3. Pine seedlings will die in a decade characterized as 'unusually dry', but maple seedlings will survive.

Aspen age is incremented in decades. Maple, once established, grow at least 3.0 m in a dry decade and at most 4.3 m in a wet decade (Table 1). Once the maple are greater than 26.0 m high on a good soil or 23.0 m high on a medium soil, they stop increasing in height.

Pine growth is described below in the Pine Frame.

Aspen do not regenerate beneath mature aspen. The probability that old aspen will die or be blown down is 0.02 times their age beyond 70. When the aspen die, the

Table 1. Estimated average growth of trees in northern Minnesota (m/decade)

Site index	50	60	70
Soil quality	Poor	Medium	Good
Red/white pine	3.0	3.7	4.3
Red/white pine—shaded	2.0	2.4	2.8
Maple		3.0	4.3
Spruce	2.7	4.0	

Modified from Carmean and Vasilevsky (1971)

model switches to the Pine Frame if there is at least one mature pine cohort present, or if pine trees are more than 3.0 m high and are taller than the maples. Otherwise, the model switches to the Maple Frame, unless there is no maple understory. In this case, aspen regenerate.

The probability of a fire occurring during a decade in the Aspen Frame depends on the time since the last fire (Table 2). The fire will be a ground fire, unless there are pine trees that are more than 9.0 m high to carry the crown fire. In this case, there is a probability, depending on the time since last fire, that the fire will be a crown fire (Table 3).

A ground fire will destroy almost all aspen and maple as well as pines less than 9.0 m high. If there are taller pines that survive the ground fire, the model switches to the Pine Frame. If no pines survive the fire, the aspen regenerate. A crown fire will kill most trees, and aspen will regenerate.

### Pine Frame

The variables in this frame are time since last fire, height of the maple understory, height of red and white pine, and the number and age of cohorts of mature pines.

Maple seedlings can establish at any time (Stearns, 1951). Pine seedlings will only become established in a decade with 'normal' rainfall, if the regenerating pine cohort has matured (is over 18.0 m high) and if the maple understory is less than a certain threshold in height, where the threshold is chosen by a random number generator in the range between 6.0 and 9.0 m. Maple grow according to the same formula as in the Aspen Frame.

Table 2. Estimated probability per decade of a wild fire in northern Minnesota

Years since last fire	Aspen	All pine and spruce—fir
10	0.00	0.00
20	0.03	0.04
30	0.06	0.08
40	0.10	0.12
50	0.13	0.17
60	0.16	0.26

Modified from Frissell (1973), Heinzelman (1973) and Heinzelman (1981)

Table 3. Estimated probability per decade of a wild fire being a crown fire in northern Minnesota

Years since last fire	Aspen and jack pine	Red and white pine
10	0.00	0.00
20	0.00	0.00
30	0.01	0.01
40	0.07	0.02
50	0.14	0.07
60	0.21	0.12

Modified from Frissell (1973), Heinzelman (1973) and Heinzelman (1981)

Pine growth following establishment is determined by soil type, browsing and competition with other trees. Based on soil type only, pine growth varies from 3.0 m to 4.3 m per decade (Table 1). Competition occurs in the Aspen Frame when aspen are less than 50 years old, and in both the Aspen and Pine Frames when the maple understory is taller than the pines. In this case, pine growth is reduced by the shade and ranges from 2.0 to 2.8 m per decade (Table 1). While the pines are less than 2.0 m high, they are vulnerable to browsing by deer. Browsing reduces their height growth by 0.9 m per decade if deer density is low, 1.8 m per decade if deer density is medium, and 3.7 m per decade if deer density is high.

Once the red and white pine reach 18.3 m in height, they become a new mature pine generation and their age is measured from the time they reached 4.6 m in height. Mature pine generations can die of old age, or if there are tree-felling winds in a decade, they may be destroyed with a probability that depends on their age (Table 4). If all mature pine generations are dead, blown down or harvested, the model switches to the Maple Frame if the maple understory is more than 2.0 m taller than regenerating pine.

Fire in the Pine Frame occurs with a probability that depends only on time since the last fire (Table 1). The probability that any fire, once one occurs, will be a crown fire, also depends only on time since last fire (Table 3). Ground fires destroy most maples and most regenerating pine less than 9.1 m high. If there are no taller pines, a ground fire will generate a switch to the Aspen Frame. A crown fire will destroy all trees and aspen will regenerate.

#### Maple Frame

The assumption is made that fires will not occur and that maple will continue to regenerate (Stearns, 1951; Whitney, 1986). Only a management decision to clear-cut and burn will have any effect on the forest. If this occurs, the model switches back to the Aspen Frame. The annual probability of a catastrophic blowdown affecting a mature maple forest is  $<0.001$  (Frelich & Lorimer, 1991). This probability is so low that it is not included in the model.

**Table 4.** Estimated probability per decade of white or red pine dying of old age or, if high winds occur, of old age and high wind combined, in northern Minnesota

Tree age	Mortality factor	
	Old age	Old age with wind
0	0.00	0.00
100	0.00	0.20
200	0.00	0.50
300	0.01	0.90
400	0.07	0.90

Wind data modified from Frelich and Lorimer (1991)

Age mortality data modified from Buchman (1983)

## JACK PINE-PINE-SPRUCE SUCCESSIONAL CYCLE

### Jack Pine Frame

The variables in the Jack Pine Frame are age of jack pine, height of the spruce understory, height of red and white pine, and time since last fire. The frame starts with bare ground on which jack pine begin to grow. Pine and spruce seedlings can establish themselves after the first 10 years. Pine seedlings will fail in an 'unusually dry' decade, but spruce seedlings will survive.

Jack pine age is incremented in decades. Once established, spruce growth per decade is 2.7 m on poor soil and 4.0 m on medium soil. Once the spruce are over 23.2 m high on a medium soil or 20.1 m high on a poor soil, they stop increasing in height.

Pine growth is as described in the Pine Frame for the Aspen-Pine-Maple cycle. This growth can be modified by browsing and competition, as described in the previous cycle.

The assumption is made that jack pine will not regenerate beneath mature jack pine (Rudolph & Laidly, 1990; Frelich & Reich, 1995). The probability that old jack pine will die or be blown down is 0.02 times their age beyond 70. When jack pine die, the model switches to the Pine Frame if there is at least one mature pine cohort, or if the pines are taller than the spruce. Otherwise, the model switches to the Spruce Frame, unless there is no spruce understory. In this case, the jack pine regenerate.

The probability of a fire in the Jack Pine Frame depends on the time since the last fire (Table 2). If a fire occurs, there is a probability, depending on the time since the last fire, that it will be a crown fire (Table 3). A ground fire will destroy most spruce, pines less than 9.0 m high, and jack pines less than 50 years old. If there are taller red and white pines that survive the ground fire, the model switches to the Pine Frame. If not, the model stays in the Jack Pine Frame and jack pine regenerate. A crown fire destroys all trees and jack pine regenerate.

### Pine Frame

The Pine Frame in this cycle is similar to that in the previous cycle.

### Spruce Frame

The variables in the Spruce Frame are time since last fire, spruce age and occurrence of a spruce budworm outbreak.

Spruce age is set at one year per 0.3 m of height (Carmean & Vasilevsky, 1971) coming into the Spruce Frame and is thereafter increased by decades. When spruce trees are 70 years or older, there is a 0.25 probability each decade of a spruce budworm outbreak. Once an outbreak has occurred, another will not occur until the model switches out of the Spruce Frame and then back to the Spruce Frame. An outbreak, once it

has occurred, increases the probability of a fire. The probability of a wild fire, all of which are assumed to be crown fires, is given in Table 2. If a spruce budworm outbreak has occurred, add 0.35 to the probabilities.

Fire kills all trees in the Spruce Frame, and the model switches back to the Jack Pine Frame. If fires are suppressed, spruce will regenerate and persist indefinitely unless the forest is clearcut and burned. In this case, the model switches to the Jack Pine Frame.

## RESULTS AND DISCUSSION

In this section, we describe results from four sets of computer experiments. In all cases, we specified the probability of high winds (capable of felling cohorts of old pines) as 0.25/decade (modified from Frelich & Lorimer, 1991) and the probability of an 'unusually dry' decade as 0.20 (modified from Baker & Kuehnast, 1978). We considered a time span of 1000 years, and performed 1000 replicates for each experiment. Since deer numbers will fluctuate during 1000 years, we postulated four deer scenarios (adapted from Alverson *et al.*, 1988): 'low deer' describes the scenario where deer density is low with probability 0.80 and medium with a probability of 0.20 in each decade; for 'medium deer', the density is low with  $p=0.67$  and medium with  $p=0.33$ ; for 'high deer', the density is low with  $p=0.50$ , medium with  $p=0.25$ , and high with  $p=0.25$ ; finally, for 'very high deer', the density is low with  $p=0.20$ , medium with  $p=0.40$ , and high with  $p=0.40$  in each decade.

### Sets 1 and 2: impact of fire, deer and soil on pine regeneration

Several researchers have concluded that fire frequency and abundance of deer have a large influence on the success of white and red pine regeneration (e.g., Maisurow, 1935; Hansen & Brown, 1950; Heinselman, 1973; Heinselman, 1981; Cwynar, 1977; Frelich, 1992). In addition, these two factors may interact differently on different soil types. Therefore, we analyzed the interaction of fire, deer and soil type (Set 1). However, since basic soil type does not change during the management history of any one stand, we also examined fire-deer effects on pine management holding soil constant (Set 2).

In Set 1, we imagine four fire scenarios: 'low fire' suppresses, at random, half of the natural wild fires; 'medium fire' allows all wild fires to burn; 'high fire' doubles the probability of wild fires; and finally, 'special fire' suppresses wild fires only if the pines in the understory are < 12.0 m high. The model assumes that pines < 9.0 m high will not survive ground fires. However, to reflect conservative management, we specified that wild fires be suppressed if pines were < 12.0 m high.

During a 1000 year simulation, the system may switch in and out of the Pine Frame a number of times. The

average total time in pine is calculated by keeping a running total of the decades spent in the Pine Frame and dividing by the number of replicates. The average residence time is calculated by recording how long the system spent in the Pine Frame before switching out again (the residence time) and averaging this over all the switches into the Pine Frame.

Figures 1(A)–(D) illustrate the effects of fire frequency and deer density on the total time in pine, expressed as years in pine/1000 years, on various soil types with and without clearcutting of maple forests. In all cases, the longest total time in pine was reached with low deer densities. In all cases except on good soil with no clearcuts (Fig. 1(C)), the longest time in pine was reached with a combination of low deer and special fire, with a maximum of 571 years in pine on medium soil when starting in the Jack Pine Frame (Fig. 1(B)).

The shortest total time in pine occurred on poor soil with high fire frequency and very high deer density (Fig. 1(A)). Under these conditions, repeated fires caused jack pine to regenerate, and deer consumed nearly all white and red pine seedlings.

Fire frequency had the least effect on good soil with no clearcutting (Fig. 1(C)). The impact of different deer densities was also minimal in this simulation. We attribute this to conversion of the site to maple forest, which will not burn and which has a suppressing effect on pine reproduction. Since there are few pine seedlings available, the impact of deer browsing is minimized. The total time in pine can be increased markedly in this simulation by clearcutting the maple forest, as shown in Fig. 1(D).

The simulated total time in pine was low on poor soil and on good soil when clearcutting was not used. Total time in pine was highest on medium soil when the succession began in the Jack Pine Frame and on good soil when clearcutting of the maple forest occurred, allowing a switch to the Aspen Frame.

To examine fire-deer interactions on one soil type (Set 2), we analyzed the impact of fire management for a site on medium soil, beginning in the Jack Pine Frame. We postulated a management strategy whereby ground fires were prescribed in the Jack Pine and Pine Frames if the height of regenerating pine cohorts was > 12.0 m, while natural fires were suppressed if the height of regenerating pine cohorts was < 12.0 m. We considered three probabilities of implementing this strategy: a 0.0 probability is equivalent to no management; a 0.5 probability represents an intermediate level of management in which there is a probability of 0.5 that the appropriate action will be taken; and a 1.0 probability represents intensive management, i.e. a rigid adherence to the strategy. In all cases, there was no fire control in the Spruce Frame.

Average total time in pine (Fig. 2(A)) appears to be only moderately affected by low, medium and high deer density, regardless of fire frequency. However, a very high deer density results in reduced total time in pine.



With 0.0 or 0.5 probability of igniting or suppressing fires, the impact of deer density on average residence time is small (Fig. 2(B)). Increasing the probabilities to 1.0 results in a marked impact of deer on average residence time. This reflects the large increase in pine reproduction that occurs under this fire regime.

Deer density appeared to have little effect on the number of wild fires suppressed (Fig. 2(C)). The number of prescribed fires implemented by the model declined with increasing deer density (Fig. 2(D)). Pine regeneration is inhibited by high numbers of deer. Therefore, most pine stands are less than 12 m in height and prescribed fires cannot be used.

### Set 3: sensitivity of the model to variations in forest conditions

We tested the applicability of the model by simulating conditions in three forest sites in northern Minnesota. The North Shore of Lake Superior was selected as representative of forests on good soil (Flaccus & Ohmann, 1964) with very high deer populations. Clearcutting in the Maple Frame was specified with a probability of 0.15/decade. Itasca State Park was selected as

representative of forests on medium soil with high deer populations (Hansen *et al.*, 1974). No clearcutting was specified. The Boundary Waters Canoe Area Wilderness (BWCAW) was selected as representative of forests on poor soil with low deer populations (Frelich & Reich, 1995). No clearcutting was specified. We considered the same fire management scenarios (with three probabilities of implementing a strategy) as in Set 2.

The average total number of years out of 1000 in white and red pine (Fig. 3(A1–C1)) varies from 186 on the North Shore with 0.0 probabilities of fire management to 714 at Itasca State Park with optimum fire management. Relationships among the three sites with reference to average total number of years in pine are similar for the three levels of fire probability, with the North Shore always being lowest and Itasca State Park always being highest. The simulation shows that the low number of years in pine on the good soil of the North Shore is due to the very high deer population, which inhibits establishment of new pine cohorts, and the strong tendency for the community to succeed to maple. The high levels at Itasca are related to the combination of medium soil and high deer. It is interesting to note that even though

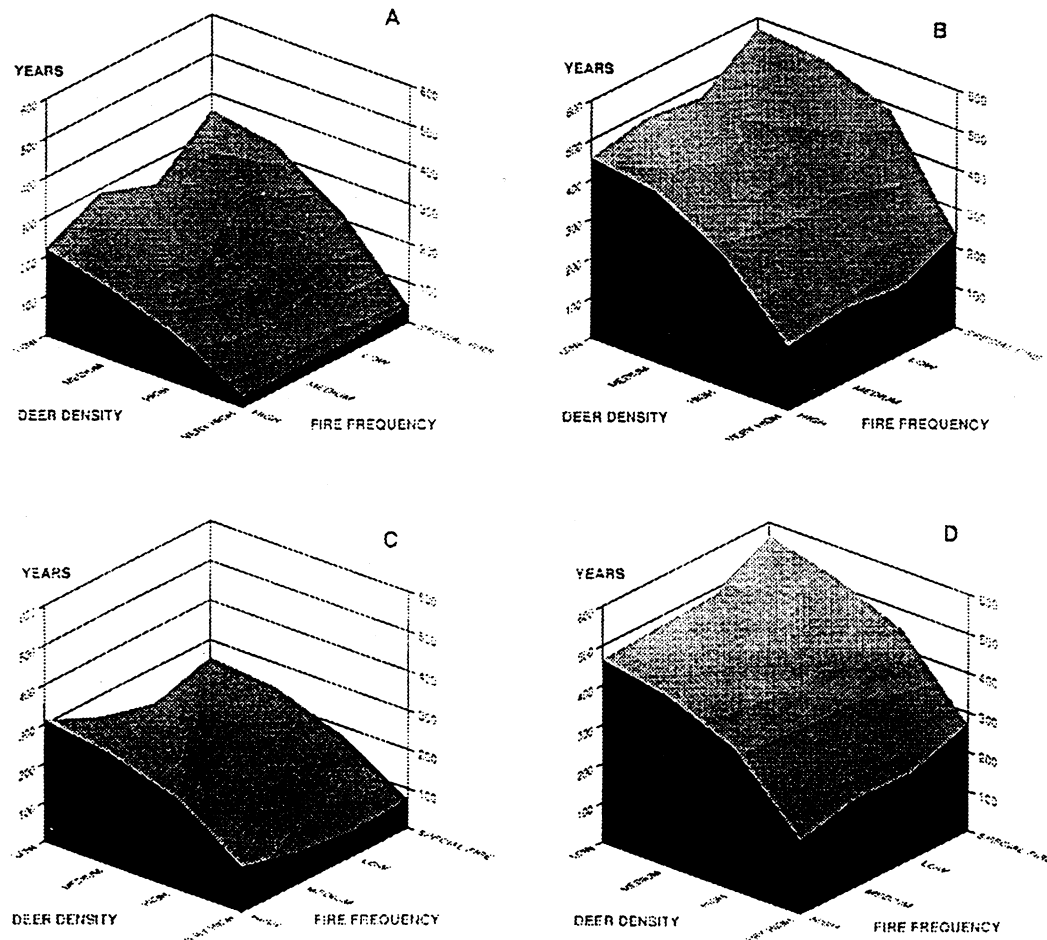


Fig. 1. Effects of fire frequency and deer density on the total number of years out of 1000 in pine on poor soil starting in the Jack Pine Frame (A), on medium soil starting in the Jack Pine Frame (B), on good soil starting in the Aspen Frame with no clearcuts (C), and on good soil starting in the Aspen Frame with 0.2 probability of clearcuts (D). Special fire frequency represents suppression of wild fires only if understory pine height < 12.0 m.



deer populations are low in the BWCAW, the poor soil limits establishment and growth of pine.

Data are not available to validate or prove that the model is an accurate predictor. However, examination of the results of the simulations for the three forest sites (Fig. 3) gives us confidence in the model. It portrays the past and present status of each of the forest sites in ways that fit with what is known from the literature (Flaccus & Ohmann, 1964; Hansen *et al.*, 1974; Frelich & Reich, 1995). Examination of model outputs not shown here (such as distributions of intervals between fires) in the various frames, further bolsters confidence in the model. Following Oreskes *et al.* (1994), our objective is not the impossible task of validating the model and then using it to make predictions, but rather the more subtle process of building confidence in it and using the results to generate insights, hypotheses and new questions. We have used the model to perform 'thought experiments' designed to provide insights into the ways in which the various stages of succession (i.e. frames in the model) respond to management strategies.

#### Set 4: factors causing loss of pine

Maintaining white and red pine in a given ecosystem depends on a balance between establishment of new trees and loss of old trees. Switching out of the Pine Frame could be caused by three factors: fire, high wind, or other factors, such as old age. We examined the frequency of switches caused by each of these factors in the three forest sites using the same probabilities described above.

With no management, fire caused 27–32% of the switches; with the probability of 0.5 management, fire caused 20–23% of the switches; and with optimum management, fire did not cause any switches.

The proportion of switches caused by other factors was quite similar for the 0.0 and 0.5 probability management scenarios, ranging from about 4 to 10% at each level (Fig. 3(A2) and Fig. 3(B2)). With optimum management ( $p = 1.0$ ), all switches were caused by wind (Fig. 3(C2)).

Wind was the most important factor causing switches at all three sites under all three management scenarios. Proportions ranged from 62% at the North Shore with

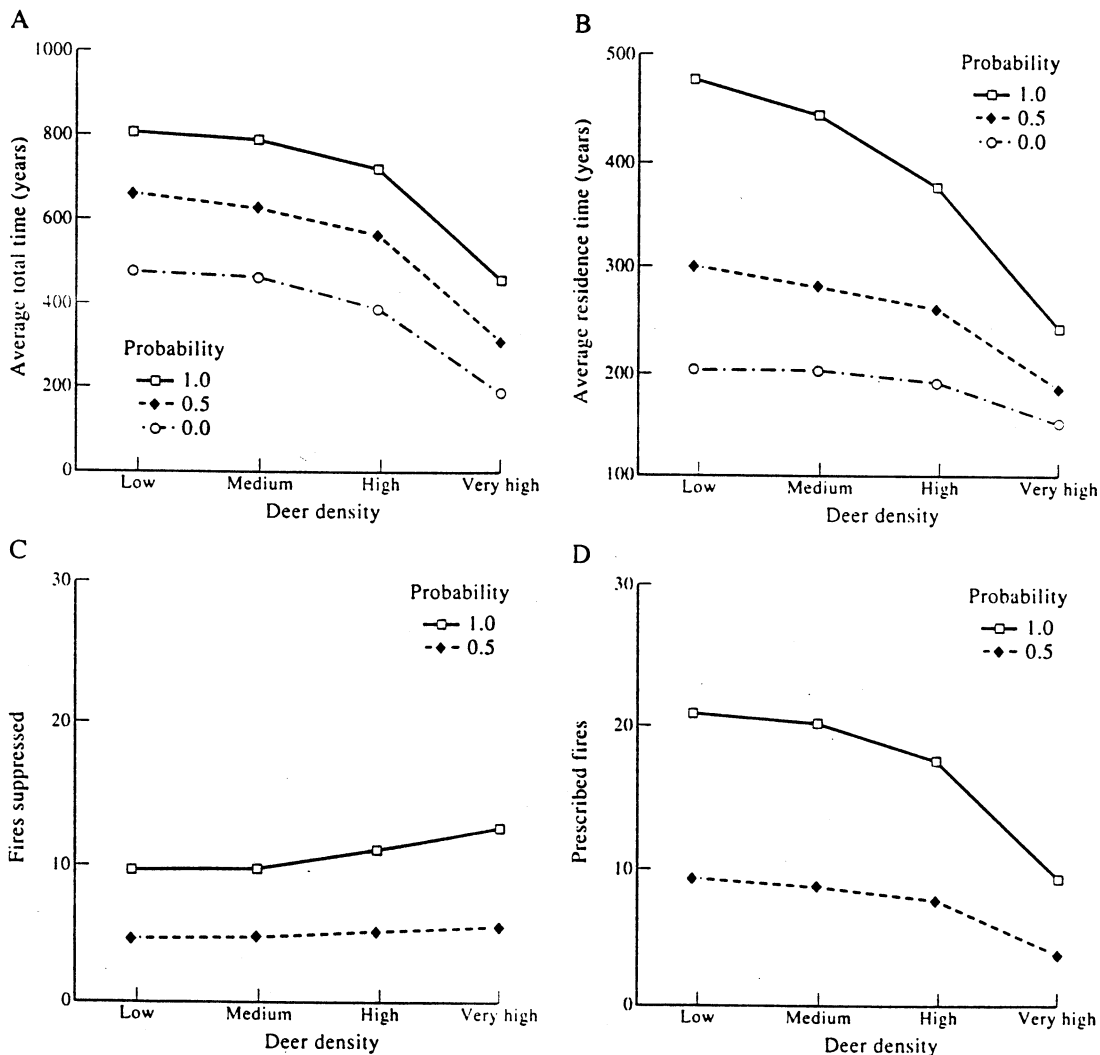


Fig. 2. Average total number of years out of 1000 in pine (A), average residence time in the Pine Frame over 1000 years (B), average number of fires suppressed during 1000 years (C), and average number of prescribed fires during 1000 years (D) on medium soil, starting in the Jack Pine Frame, with varying probabilities of suppressing wild fires and prescribed burning if pine height > 12.0 m.

no management to 100% at Itasca with optimum management. The proportion of pine stands lost due to wind is higher under optimum fire management because the factors other than wind are somewhat controlled by management. Under optimum management, pine stands are converted to other species less often, but when they are converted, the only factor over which people have no control—wind—is highly likely to be the cause.

The importance of wind in removing old pine cohorts is expected. Based on long-term observation at 11 weather stations in the Great Lakes Region (Simiu *et al.*, 1979; Changery, 1982), winds of 100–120 km/h occur about every 100 years at a given location. Such winds are likely to cause the removal of older cohorts of trees without leveling an entire stand (Frelich & Lorimer, 1991). Because the senescence process in white

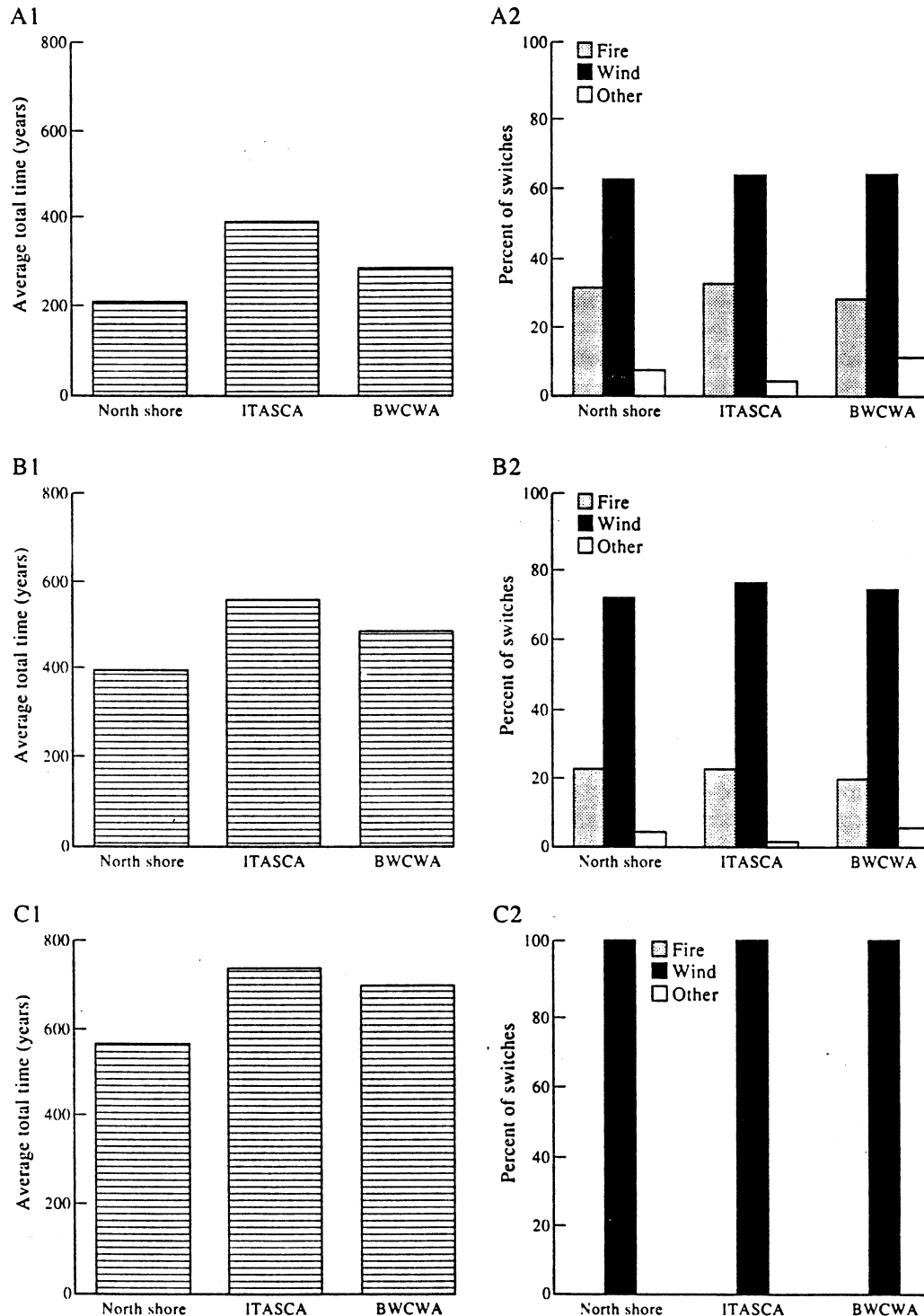


Fig. 3. Total number of years out of 1000 in pine (A1, B1, C1) and percent of switches out of white/red pine caused by fire, wind, or other factors (A2, B2, C2) in the previous decade with varying probabilities of suppressing wild fires and prescribed burning on good soil at the North shore, on medium soil at ITASCA, and on poor soil at BWCWA. A:  $p = 0.0$ , B:  $p = 0.5$ , C:  $p = 1.0$ .

pine takes many decades, old and weakened trees are likely to blow down or be snapped off before dying of old age.

## CONCLUSIONS

Management implies choice and choice implies a means of comparing alternative plans or strategies. Modeling is a tool for taking the best current understanding and information and combining them to explore the likely consequences of different management actions. Population models are relatively easy to construct and are regularly used to help plan the management of endangered and exploited species. Ecosystem management has recently become an important, if somewhat vague, conservation goal. Part of the vagueness might be attributed to the difficulty of constructing relevant ecosystem models. Ecosystem models tend to be either too simple because they do not model key processes explicitly, and hence cannot be used to explore different management manipulations, or too complex because they do indeed model processes, but at a level of detail that requires too much input data and does not readily scale upwards from a small to a larger patch. The frame-based modeling paradigm, used in this paper, is an effective compromise between these two extremes. It lends itself to rapid prototyping: a model that captures the key events and processes can be constructed quickly and efficiently. This first prototype then can be used to test the relative importance of the features included in the model, to identify model output that is likely to be useful to managers and to demonstrate the broad trade-offs between alternative management actions. Because the investment in the first prototype is small, it can be rejected and redesigned if it is unsuccessful. Because the modeling paradigm is top-down, the first prototype can be expanded into a second prototype by adding relevant details. The key to this approach is that, at any stage, there is a working model that can be exercised and tested to see if it is at the appropriate resolution for the management questions that are being addressed.

The results indicate that the understanding of interactions among physical factors (such as soil, fire and wind) and biological factors (such as deer numbers) is essential in developing management plans for effective establishment of red and white pine forests. The model is, we hypothesize, at the right scale, and contains the right processes, to provide managers with a first approximation of how these forest ecosystems respond to alternative management actions. Details, such as nutrient cycling, which are important on a smaller scale, need only be represented in this type of model implicitly (for example, in the rates and rules for the development of the understory).

Our results confirm the well-known principle of forest management that it is comparatively easy to maintain a forest in early successional stages by burning or clear-

cutting, and in late stages by suppression of fires and control of cutting. Much more difficult is the establishment and maintenance of mid-successional stages, such as red and white pine, which require a finely-tuned disturbance regime. The model is useful for examining possible strategies for maintaining mid-successional white pine forests. For example, in the case of a stand on medium soil with a high deer population, and the absence of any management actions, the probability of remaining in the Jack Pine Frame, switching to the Spruce Frame, or switching to the Pine Frame is a function of the time since a major disturbance that initiated the Jack Pine Frame (Fig. 4(A)). We can improve the likelihood of switching into the Pine Frame when we apply our intensive management strategy (Fig. 4(B)). Finally, Fig. 5 shows how the intensity of management influences the probability of staying in the Pine Frame once we have switched into it.

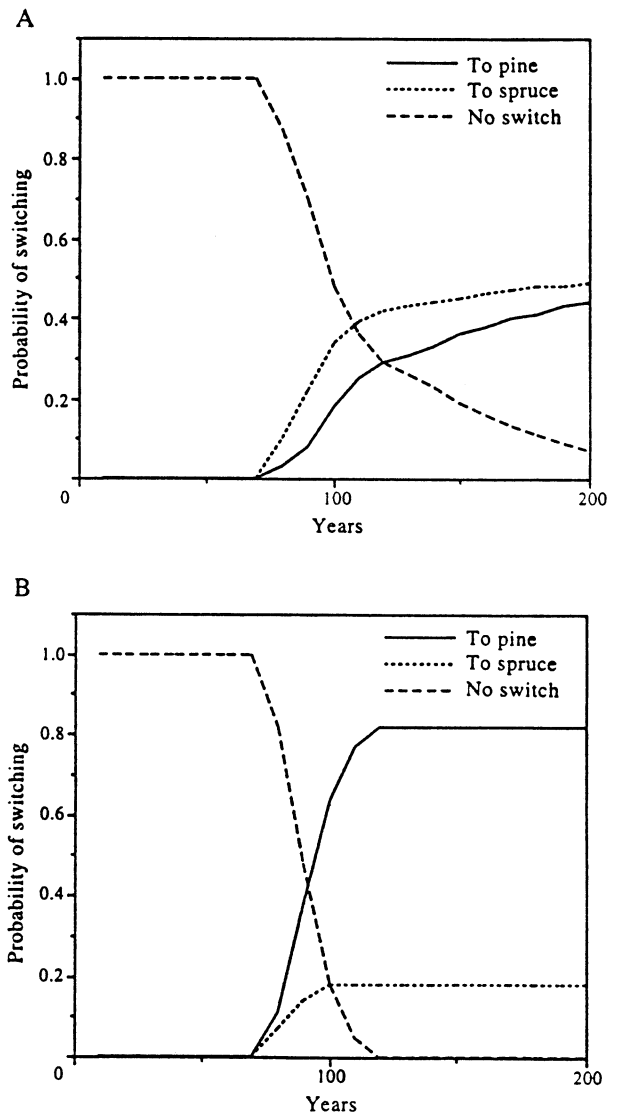


Fig. 4. Probability of switching out of the Jack Pine Frame over time with no management (A) and with optimum management (B) on medium soil with a high deer population and probability of high wind of 0.25/decade.

These results, as do all the model results, suggest that the interplay of natural factors (such as wind) and management actions can be complex even though the underlying model is simple. Our model experiments generate the following thoughts about management of this ecosystem:

1. A successful management policy combines a blend of fire promotion, fire prevention and deer control. There is no simple management solution such as 'put out all fires'.
2. There are limits to what management can achieve. Soil type, for example, is an important determining factor: it is easier to manage so as to promote white and red pine on medium and good soils than on poor soils. Wind also plays an important role in accelerating conversion of pine to late successional species.
3. Success is measured in hundreds rather than tens of years. Moreover, management strategies lose their impact if they are not rigorously maintained. It follows that ecosystem management needs to develop a long-term perspective that is quite different from one where the prevailing management paradigm changes every few years. It also follows, especially in light of point 2 above, that climate change could have a strong impact both on what managers will need to do (frequency of fire control, for example) and what they will be able to achieve.

This exercise illustrates what can be deduced from a parsimonious model developed using a frame-based, top-down approach. (It should be noted that this paper contains a complete description of the entire model.) One can, of course, continue to add detail to the model within the structure of the frames. A more detailed

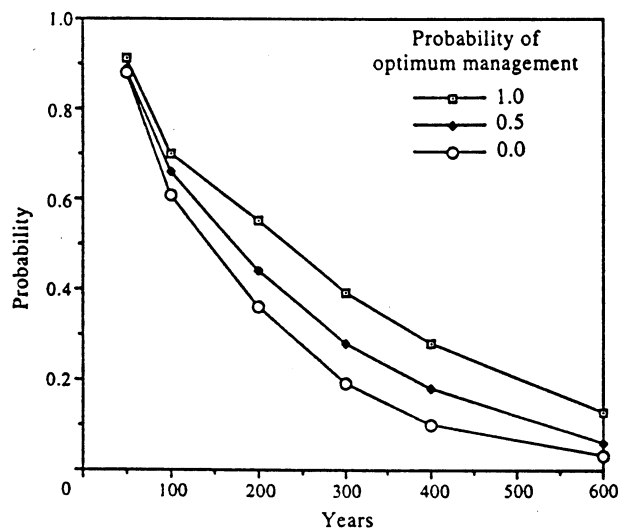


Fig. 5. Probability of remaining in the Pine Frame over time with varying probabilities of suppressing wild fires and prescribed burning on medium soil with a high deer population and probability of high wind of 0.25/decade.

model might provide information on aspects of ecosystem functioning, such as carbon storage, nitrogen mineralization, and other aspects of productivity and nutrient cycling. However, we question whether this type of information would be of value to persons concerned with management of pine ecosystems on a landscape scale. What would, however, be useful to managers would be an expansion from the single patch model presented here to a multiple patch landscape. Our approach lends itself to such an expansion: frame-based models appropriate to the soil type (and aspect) could operate on each patch, with different patches at different stages in the successional sequence. Such an expansion would include representation of seed availability, fire spread and deer movement between patches, and evaluate ecosystem management strategies at an even more realistic scale.

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